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Aerosol Characterization of Abrasive Blasting Operations

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◢ ABSTRACT

Abrasive blasting in aircraft maintenance generates complex aerosols with significant health implications due to hazardous compounds like hexavalent chromium. Critical knowledge gaps persist regarding particle size distribution and composition for accurate exposure assessment. This study provides a detailed aerosol characterization of these environments using a multipronged approach: real-time particle size distribution analysis, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and inductively coupled plasma (ICP) analysis. The results from analyzing bulk dust and inhalable (IOM) samples showed that the bulk dust particles span 20−244 µm, with chromium concentration peaking at 0.29% in the 40−60 µm fraction. EDS confirmed chromium and strontium (indicating aircraft primer) primarily on smaller particles. Metallic contaminants were detected in plastic media operations but absent with steel media. Critically, we challenge the validity of standard correction factors for historical 37-mm closed-face cassette (CFC) data, demonstrating that non-uniform hazardous particle distribution risks over or underestimating exposures. These findings necessitate size-resolved sampling and correction factors between CFC and IOM data. Future work with cascade impactors is recommended to resolve aerosol distribution profiles for evidence-based conversion factors. This research provides a foundation for safeguarding DOD maintenance-shop workers' health and informs policy transitions to modern sampling.

KEY WORDS: *abrasive blasting, aerosol characterization, hexavalent chromium, inhalable sampling, particle size distribution, occupational exposure*

◢ INTRODUCTION

It is well established that particulate matter in the workplace poses health hazards to unprotected workers. Like gas and vapor contaminants, the concentration and composition of the particulate matter determine the severity of the hazard; however, the distribution of particle sizes also contributes to potential health effects (Mirowsky, 2013; Lippmann, 1999; Kan, 2018). Due to the increasingly narrow branches that make up the lower respiratory tract, only particles up to 4 µm can penetrate the alveolar region of the lungs (Phalen, 1999). Coarse particles ≤10 µm penetrate the thoracic region, and particles larger than 10 µm up to 100 µm penetrate primarily to the upper airways and nose (Phalen, 1999).

Particle size selective (PSS) samplers are designed to mimic the penetration of particles in the respiratory system by abiding a 50% cut point at 4 µm, 10 µm, and 100 µm for respirable, thoracic, and inhalable particles, respectively (Raabe, 1999; Vincent, 1999). It is policy for the American Conference of Governmental Industrial Hygienists (ACGIH) to include PSS guidance for new threshold limit values for aerosol contaminants.

ACGIH recently recommended sampling for hexavalent chromium using a sampler that adheres to the inhalable convention, since large chromium containing particles that deposit in the nose can cause painful ulcers (ACGIH, 2018). In the Department of Defense (DoD), hexavalent chromium exposure is most often found in corrosion control operations during painting and de-painting aircraft and their components (Carlton, 2003; Bennett, 2016; Bennett, 2018). While aerosol size and composition during painting operations have been established, little data are available on the characteristics of the dust generated during abrasive blasting procedures, with estimates of particle size ranging from 1-1,000 µm (Carlton, 1997; Sabty-Daily, 2005; Carlton, 2000).

Aircraft maintenance and associated processes impact a large workforce and generate a high volume of samples. The bulk of prior exposure data was collected using 37-mm closed-face cassettes (CFCs). These cassettes, designed prior to PSS practice, do not adhere to any health-based size convention but instead have efficiencies that drop precipitously at larger particles sizes, with a reported efficiency of 7% at 38.7 µm compared to the 55% dictated by the inhalable convention (Witschger, 2004; Vincent, 1999). This is in stark contrast with the performance of the best-known inhalable sampler, the Institute of Medicine (IOM) sampler, which closely approximates the inhalable convention. To compare historical data with data obtained using an IOM, it has been proposed that industrial hygienists apply a correction factor to account for the under sampling inherent in the CFC's design (Vincent, 2007). The issue with this assumption is that it is based on additional assumptions, including consistent composition of the particulate across the entire size distribution. As the Air Force considers adopting inhalable sampling for corrosion control operations, it would be prudent to verify some of the underlying assumptions associated with the standard correction factor so as not to over- or under-estimate past exposures.

This study focused on characterizing the dust generated during abrasive blasting procedures using real time particle size distribution data, IOM samples, and a bulk dust grab sample. The samples used a multipronged analytical approach which included microscopic imaging, EDS, elemental composition through ICP, and real-time size distribution data based on optical particle counting.

/ METHODS

A single bulk dust sample and five IOM filters were analyzed via SEM with EDS to determine particle size distribution and surface composition. Bulk dust underwent additional elemental chromium analysis by ICP.

2.1 Bulk Dust Analysis

A 44.4 g bulk dust sample was taken from an abrasive blasting booth and sieved (Precision e-forming, Cortland, NY) into five fractions: >126 µm, 80-125 µm, 60-79 µm, 40-59 µm, and 20-39 µm. Each section was weighed and transferred to plastic cylinders compatible with acid digestion. The samples were digested and run through an ICP for elemental chromium (i.e., all valence states) at a third-party lab.

Prior to digestion, representative subsamples from each fraction were mounted on SEM stubs with conductive carbon tape. As the blasting media was primarily composed of plastic, a nonconductive material, it was expected that a "charging" effect, where electrons load on the surface and fail to dispel causing areas of white, would be observed (Shaffner, 1970). The stubs were sputter-coated with 10 nm of gold to provide a continuous conductive surface to minimize charging while imaging. Imaging of each stub included four non-overlapping sections at a consistent magnification. Due to the polydispersity of the largest size fraction, three samples were mounted. From each of these stubs, three images were taken, and the nine images were processed together.

2.2 IOM Filter and Dust Analysis

Five IOM cassettes with polycarbonate filters were pre-weighed, calibrated to 2 LPM, and deployed during abrasive blasting operations (30 min. sampling). The samples were shipped back to the lab and the post-weights recorded for the filter and the dust retained on top of the filter.

The filters were returned with details surrounding the conditions under which they were collected (Table 1). Four of the five samples collected were from booths that used plastic beads as the abrasive material and one sample was taken in a booth with steel media.

TABLE 1
IOM Filter Collection Parameters

Filter ID	Blasting Media	Number of Blasters	Sample Collection Time (min)
A	Plastic	1	31
C	Plastic	2	34
D	Steel	2	30
F	Plastic	1	34
G	Plastic	2	29

While the bulk on top of the filters did not appreciably differ between the plastic media samples, the steel media produced a powdery gray solid which was in stark contrast to the plastic media bulk (Fig. 1).

The filters were sputter coated with 10 nm of gold and then imaged using EM-Tec F25 filter sample holder (Rave Scientific, Somerset, NJ) which allowed for processing the entire filter instead of an excised portion.
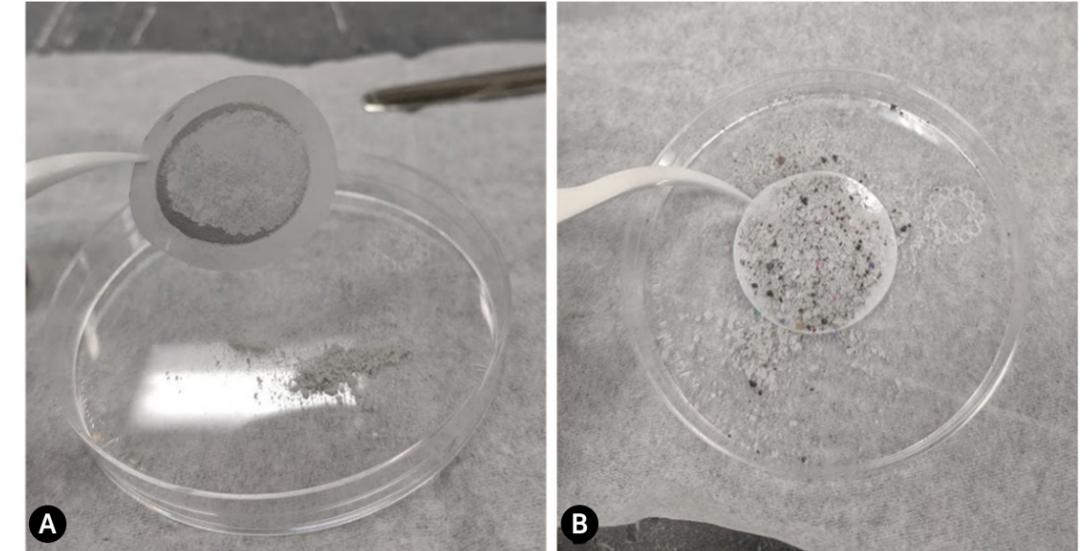

FIGURE 1
IOM Filters and Bulk Media. A) Bulk Material from Steel Media; B) Bulk Material from Plastic Media

2.3 Image Analysis

All samples were analyzed on a JSM-IT500 (JEOL, Tokyo, Japan) scanning electron microscope. Bulk dust samples were loaded on 10 mm aluminum stubs with conductive carbon tape. Whole filters were mounted on a 25-mm disk holder (Rave Scientific, Somerset, NJ).

2.3.1 Bulk Dust

The researcher processed all SEM images with open-source software ImageJ (NIH) using the pre-packaged application Fiji (v. 1.52q). For images gathered from the bulk dust stubs, automatic particle processing was not possible. The auto-characterization function relies on the ability to turn any image into binary, which itself depends on strong contrast between the particle edge and the background. Despite the layer of gold coating on the stub, charging was an issue during imaging, which resulted in areas of pure white juxtaposed with areas of varying shades of grey. Despite the researcher's bests efforts to manually set thresholds and the use of auto-thresholding techniques available in the ImageJ package, it was not possible to capture crisp outlines for most particles.

Instead of turning each image to binary, the researcher manually outlined each particle using the freehand selection tool, used ImageJ's measurement tool, then filled in each particle with white to prevent the accidental characterization of the same particle twice.

The built-in measurement function allowed for great flexibility in capturing unique parameters associated with an individual particle. The researcher selected eight measurements: area, circularity, Feret's diameter, Feret's angle, the minimum Feret diameter, aspect ratio, roundness, and solidity. These quantify particle geometry as follows: Feret's diameter (maximum caliper distance) and minimum Feret diameter (minimum caliper distance) define size extremes; Feret's angle describes their orientation. Circularity ($4\varpi \cdot$area/perimeter^2; 0–1 scale) and roundness (1/aspect ratio) measure deviation from circularity, while solidity (area/convex hull area; 0–1 scale) characterizes surface concavity.

2.3.2 Filters

Due to the more homogenous surface of the small particles on the filters, the 10 nm layer of gold greatly reduced charging effects. This reduction in charging allowed for higher contrast images which, in turn, allowed for automated image processing using the ImageJ as described above. Due to the 0.8 µm pores of the polycarbonate, an artificial lower size cut off of 0.5 µm2 was used to prevent ImageJ's automatic particle identification feature from incorrectly classifying pores as particles.

The grey particulate on top of Filter D was dense enough that individually resolving particles was impossible, therefore the filter was excluded from imaging analysis. Filter A was damaged during specimen mounting, leading to a wrinkled surface that proved impossible to image and its exclusion from the size distribution analysis. It was possible to conduct EDS analysis for all five filters.

2.4 EDS Analysis

All samples were analyzed on a JSM-IT500 (JEOL, Tokyo, Japan) SEM equipped with an X-maxN 80 EDS (Oxford Instruments, Concord, MA). Each imaged stub was also analyzed for elemental composition. Point analysis, which was used as the gold coating, dominated the response for mapping. A minimum of 100 random points spread over the surface of the stub were analyzed for each size fraction or IOM sample. While EDS was performed in the same area as the imaging, all imaging locations were randomly selected. The microscope included a feature where previously visited spots were marked to ensure no overlap in images or EDS. The percent of measured points containing an element were determined by dividing all points containing the element of interest by the total number of particles measured for the filter.

2.5 Size Distribution

Using the projected area estimated from the ImageJ processed images, the physical diameter of the particles was estimated using the equation below (Eq. 1) (Fan, 1998) where A is the area of the particle.

EQUATION 1
Particle Physical Diameter

$$D_p = 2\sqrt{\frac{A}{\pi}}$$

Once the physical diameter was calculated, histograms for each sieve section or filter were generated.

For sieved fractions, bins were generated in five micrometer intervals until counts dropped off. For filter samples, bin intervals varied from 0.8-10 µm. Bins were then normalized by their range, then these normalized values were converted to frequency/µm by dividing by the total number of particles counted. The count median diameter (CMD) was calculated by first determining the cumulative fraction of particles by bin. The 50th percentile was interpolated from the nearest fractions. The geometric standard deviation (GSD) for each fraction was determined using Eq. 12 (Hinds, 1999).
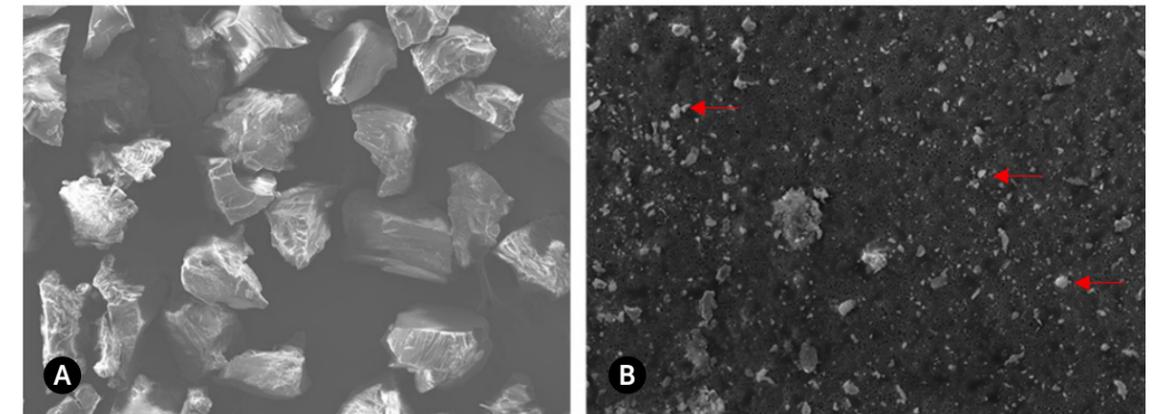
EQUATION 2
Aerosol GSD

$$GSD = \frac{(50th\ percentile)}{(16th\ percentile)}$$

RESULTS

While charging was an issue with the bulk dust samples, micrographs showed no areas of brightness indicative of metals (Fig. 2A).

FIGURE 2
Micrographs: A) Bulk Dust; B) IOM Filter F, Red Arrows Showing Bright Particles.

Combined with EDS results, this confirms bulk dust primarily comprised of plastic blasting media rather than metal-containing paint chips. In contrast, the particles on the IOM filters, when viewed with the SEM, did show areas of brightness that when analyzed with EDS showed evidence of metal compounds (Fig. 2B). The brightness of these smaller, metallic particles is due to their greater ability to backscatter electrons as they have a higher atomic number. The distribution for each bulk dust size fraction is shown in Fig. 3. Significant overlap exists between all size fractions, as sieving relied on separation based on physical diameter rather than aerodynamic diameter.
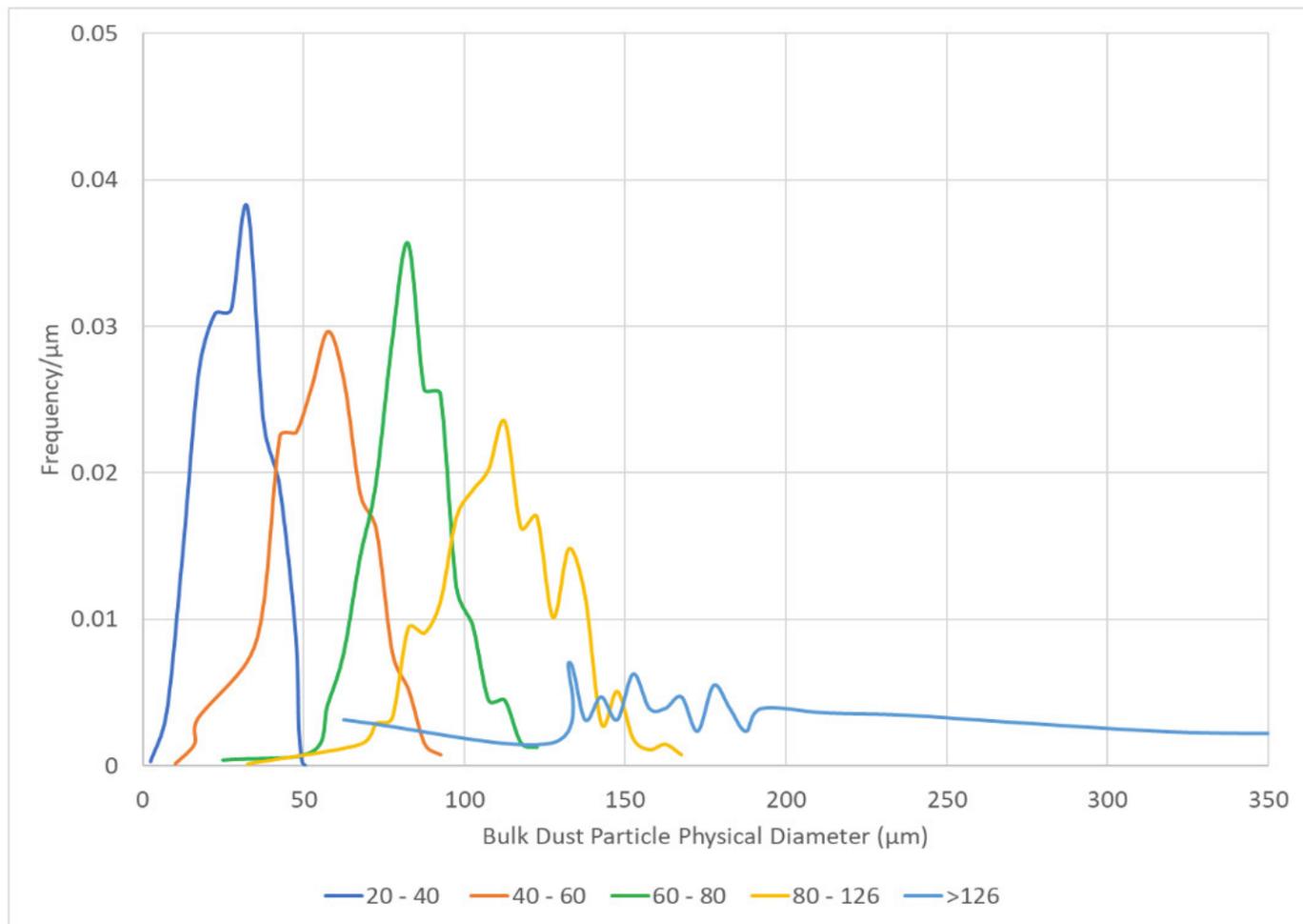
FIGURE 3
Size Distribution for Each Sieve Fraction

The CMD and GSD for the bulk dust were determined by fraction (Table 2). All GSDs were below two, indicating a relatively tight distribution, despite the heterogeneous appearance of the particles in each fraction. While the shape of the largest size fraction (>126μm) was unusual, when the log transformed frequency/μm values were evaluated using the Shapiro-Wilkes test, the results indicated a lognormal distribution. This finding validates the calculation method for finding the CMD and GSD.

The sieved fraction of bulk dust sent off for percent chromium content through ICP analysis showed an increase in chromium as particle size decreased (Table 3). Particles were sieved, placed in flat-bottomed tubes, then weighed.

Size Range (μm)	CMD (μm)	GSD
20-40	26.3	1.8
40-60	53.4	1.4
60-80	80.4	1.2
80-126	108.7	1.2
>126	244.1	1.6

TABLE 2
CMD and GSD for Bulk Dust Size Fractions

Size (μm)	Result (mg/kg)	Total Mass of Fraction (g)	Mass of Cr (mg)	Percent Cr
>126	64	43	2.752	0.006%
80-126	550	1.3	0.715	0.055%
60-80	2400	0.13	0.312	0.240%
40-60	2900	0.05	0.145	0.290%

TABLE 3
Elemental Cr Content of Sieve Fractions by Metals by ICP

EDS identified 25 elements in total among the sieved fractions (Fig. 4A). Results from EDS of the primary compound of concern found in aircraft primer—strontium chromate—showed that the highest percent of chromium was associated with the highest percent of strontium (Fig. 4B). The percentages shown correspond to the number of particles sampled that had a positive match for the element normalized by the total number of particles sampled for sieved fraction.
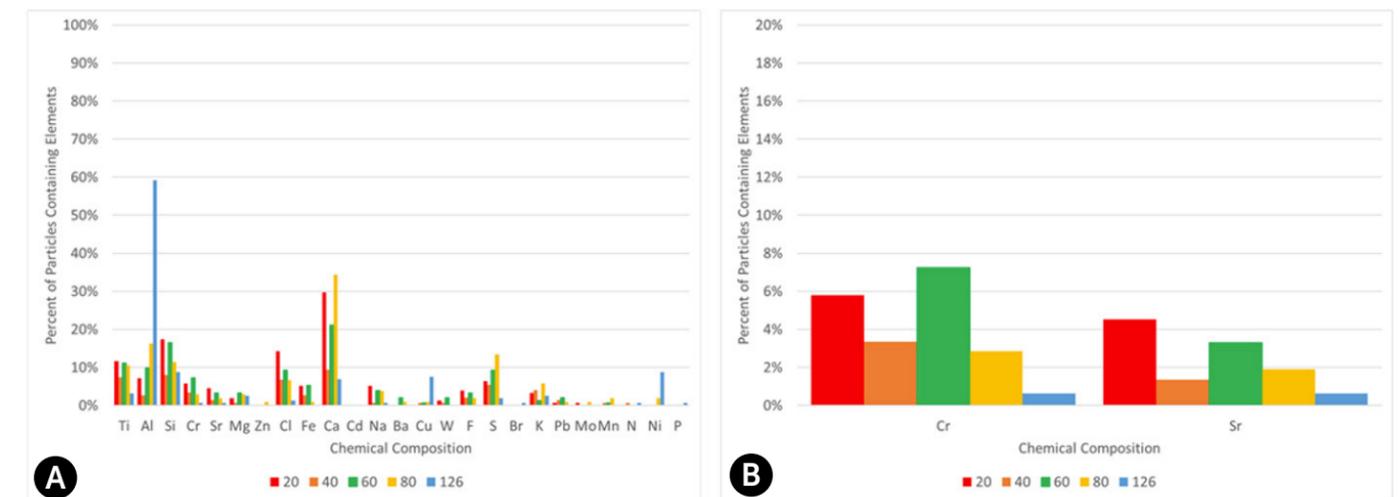

FIGURE 4
EDS Results of Bulk Dust: A) All Identified Elements; B) Elements Known to Exist in Aircraft Primer.

The distributions for filters C, F, and G are shown in Fig. 5. All distributions were truncated due to the cutoff introduced through image analysis. Due to the incomplete distribution, the CMD and GSD were not calculated.

The CMD and GSD are predicated on knowing the median particle size. Without seeing the full distribution, which should resemble a skewed normal curve, it is not possible to assert where the median lies.

FIGURE 5

FIGURE 5
Size Distribution for Filters C, F, and G (Plastic Blast Media Depainting Operations).
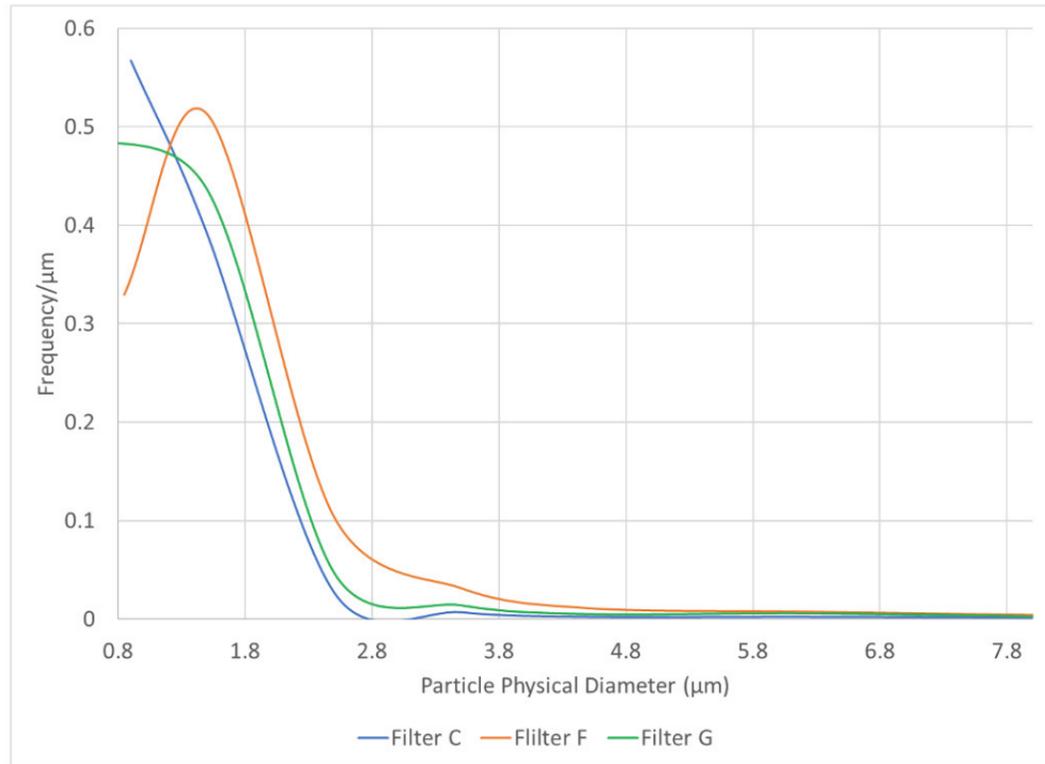
As with the bulk samples, EDS identified 25 elements in total among the five filters (Fig. 6A). The percent chromium identified did not correlate with the strontium (Fig. 6B). It is of interest to note no chromium or strontium was found on Filter D, the only IOM sampled from a blasting booth using steel media. It seems likely the part being blasted did not contain a layer of primer.
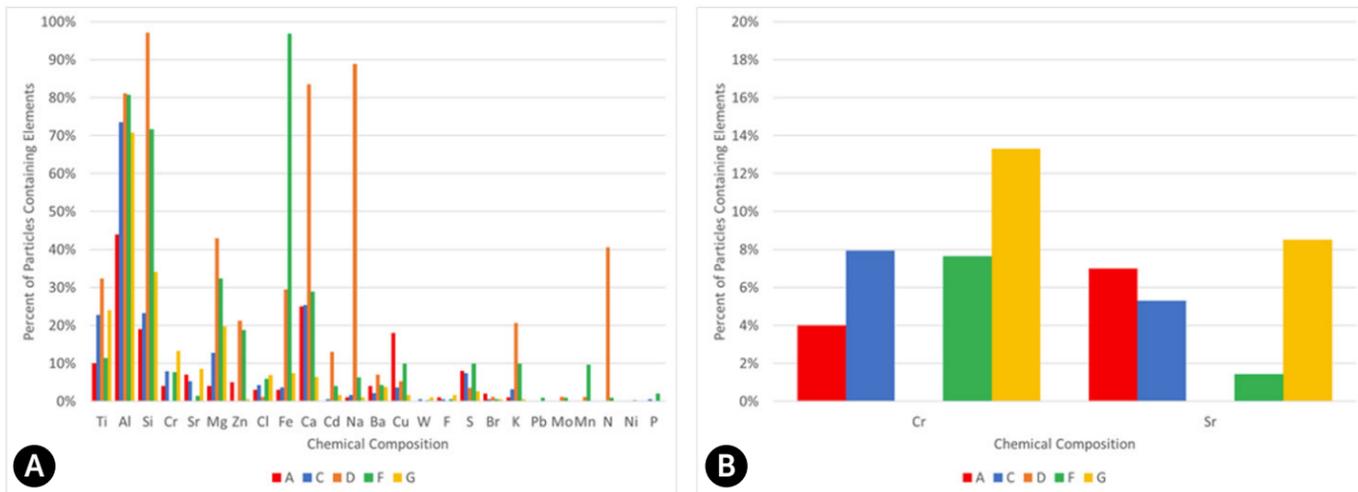

FIGURE 6
Elemental Analysis of IOM Samples via EDS: A) All Elements Identified; B) Elements of Concern in Aircraft Primer.

DISCUSSION

A key limitation of this study was reliance on a single bulk sample, restricting generalizability. At present, it is not appropriate to extrapolate the composition and distribution profile across all blasting booths or processes; however, the results obtained do indicate that chromium likely adhered to large particles and those large particles have been observed in the IOM capsule. While a correction factor could not be obtained from the single bulk sample, the ICP analysis indicates that elemental chromium concentration is not linear across all particle sizes nor proportional in a predictable way.

The impact of the limitation introduced during image processing for determining the particle size distribution for those particles adhered to the IOM filter was evident. A more appropriate technique would be to separate particles via a cascade impactor to remove the very large particles, then follow the impactor outlet with an electrometer in order to count and deposit the small particles on a TEM filter. The increased resolution and negligible pore size of the TEM filter would allow for image processing of submicron particles without relying on an artificial area cutoff.

Only a single filter was available from a steel blast media process, and the particulate generated was significantly different in size, shape, and composition from the particulate in plastic blast media samples. While the lack of chromium and strontium in the EDS analysis suggests the particular operation sampled did not involve primer, if other steel blasting operations do involve de-painting, the plastic media distributions and composition would not be generalizable.

All methods used to analyze for chromium did not evaluate valence state, only presence of elemental chromium. While in principle it was more conservative to use this approach, future research should include a validation that hexavalent chromium is the only valence present.

Future research that includes a larger study sample size and impactor samples would improve understanding surrounding abrasive blasting processes and build on the findings presented here.

CONCLUSIONS

The size distribution of particulate matters when it comes to potential health effects. For hazardous compounds with detrimental impacts to the nose and upper airways, aerosol sampling using an inhalable sampler is appropriate to measure exposure. The findings from this project indicate abrasive blasting aerosols are heterogeneous and complex. A simple correction factor to convert historical CFC values is likely inappropriate and would overestimate prior exposures.

For an organization as large as the Department of Defense, the decision to move to inhalable sampling represents an enormous commitment of time and resources both for samplers and analysts. To avoid losing decades of exposure data when making this change in sampling, efforts should be made to equate prior CFC data with what an IOM would have collected. The impulse to use a convenient conversion factor should be scrutinized, however, as it could unreasonably bias estimates. The voluntary switch to the more conservative TLV represents an admirable intent to protect workers. It would be a disservice to the spirit of the endeavor to overcorrect past samples if a reasonable alternative exists. Using the methods outlined in this study with the addition of a few key pieces of equipment, a larger study could answer the distribution question and provide an evidence-based correction factor.

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Farmers' Ergonomic Risk Assessment (FERA) Tool in the Musculoskeletal Disorders Risk Assessment of Agriculturists

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/ ABSTRACT

The awkward postures and repetitive movements of farmers during regular operations and activities could pose a significant risk of developing musculoskeletal disorders (MSDs). The purpose of this study was to assess ergonomic risk using the newly developed Farmers' Ergonomic Risk Assessment (FERA) tool and compare it with the Rapid Entire Body Assessment (REBA). During the development phase of using FERA to assess ergonomic risk, 120 rubber plantation farmers from the Udon Thani, Roi Et, and Ubon Ratchathani provinces in northeastern Thailand were selected through cluster sampling. Data were collected using the MSDs Severity and Frequency Questionnaire (MSFQ), the REBA, and the FERA. Farmers who had musculoskeletal discomfort stated that the highest severity was found in the shoulders, upper back, and hands/wrists (73.30%), followed by the lower arm (71.60%) and the neck (70.00%). The results showed that ergonomics risk assessed by FERA was found at the very high-risk level, with an operational posture that should be improved immediately (43.30%), while REBA also showed a very high-risk level (43.30%); this was followed by the high-risk level found by FERA (33.30%) as well as the high-risk level found by REBA (35.00%). FERA was statistically related to the REBA tool with linearity (Rho = 0.863, p-value < 0.001); the intra-rater reliability of the assessor, measured as an ICC value, was 0.995, while that of the farmer was 0.977, and between the assessor and the farmers' self-assessment, the inter-rater reliability was 0.971. The FERA would therefore be a very useful tool for ergonomic risk assessment among farmers performing self-assessments.

KEY WORDS: *ergonomics, risk assessment, musculoskeletal disorders, FERA, agriculture*

/ INTRODUCTION

At present, the occupational group of farmers consists of informal workers who have no social security from work and are at risk for most health conditions involving musculoskeletal disorders (MSDs). The nature of rubber farmers' work, which involves repetitive gestures and movements over extended periods while performing a wide range of operations, may have long-term health implications.

In the previous study on musculoskeletal disorders in the rubber farmer group of the Ubon Ratchathani province, we found that in the previous month, farmers had experienced a very high level of discomfort, which was determined by the frequency and severity of MSDs. The top three symptoms were discomfort in the lower back (22.52%), hands and wrists (13.92%), and knees (16.14%) (Chaiklieng, 2021). Ergonomics risk assessment with the Rapid Entire Body Assessment (REBA) tool is suitable for job types with a whole-body working posture, as it considers the position and movement characteristics of body parts and can be used for rapid and systematic assessment (Hignett and McAtamney, 2000). A REBA tool was used to assess the following ergonomic risks: lifting, carrying, moving objects with repetitive behavior, and postures involving tiptoes, leaning, and repetitive short twitching of the wrist over long periods of time. It was found that farmers were at high risk in the rubber tapping process, which was a high-risk job that should be improved immediately (Khanaphan et al., 2019). Moreover, moving rubber to sell by car, relaxing fewer than three hours per day, and lower hand compression performance had statistically significant correlations with a high risk of MSDs (Chaiklieng et al., 2020).

The previous research on REBA-based ergonomics risk assessment in rubber farmers in the Ubon Ratchathani province showed that they were at very high risk, which requires corrective action in the rubber tapping process (Chaiklieng et al., 2020). A study of the results of the ergonomics risk assessment by REBA found that these farmers had the highest risk of all (level 4) (Khanaphan et al., 2019), which was a very high risk, indicating that the problems of rubber farmers should be improved. Another study confirmed the REBA analysis result (11 points), meaning that rubber farming was high-risk work (Mattharak et al., 2011). In general, the MSDs risk was assessed using unidirectional tools such as questionnaires of MSDs on different body areas, physical fitness tests (Homsombat and Chaiklieng, 2017), or observing posture using the REBA technique. To date, no reliable technique for assessing the risk to farmers in operations has been established. Therefore, extensive research was done to develop the variables and risk levels included in the Farmers' Ergonomic Risk Assessment (FERA) tool. The objective of this study was to assess the ergonomic risks with the developed FERA tool and compare its results to those of the REBA. It could be useful in the protection against and health surveillance of MSDs, which may continuously arise from the farmers' work.

/ MATERIALS AND METHODS

2.1 Population and Subjects

This was a cross-sectional descriptive research study, and the population used in this study were farmers in the northeastern region who were registered as rubber planters. The inclusion criteria were as follows: 1) being a farmer registered in the district; 2) being a person with Thai nationality aged 20 years and over; 3) being able to read and write Thai; 4) voluntarily participating in the research project. The exclusion criteria were as follows: 1) being a farmer who had been involved in a severe accident or had undergone surgery that caused skeletal and muscular disorders; 2) being a pregnant farmer.

The study of the sample group was divided into two phases: the creating of an assessment tool phase, involving 60 people from the Udon Thani and Roi Et provinces, and a development phase, which was used as a tool to assess the ergonomics risk related to the farmers' working posture, involving 60 rubber plantation farmers from the Ubon Ratchathani province. The subjects were randomly sampled using a cluster sampling method in the northeastern region, which is the region with the most registrations as rubber planters. The sample size calculation in the case of an unknown population (Jirawatkul, 2008) was used to estimate the number of farmers to be used in the study. The proportion at high ergonomic risk, based on a previous study of rubber farmers in the Ubon Ratchathani province (Khanaphan et al., 2019), which consisted of those working in the rubber tapping process, was 0.87. This study required a sample size of at least 58 people. Ultimately, this study employed a sample group of 120 farmers from Udon Thani and Roi Et (n=60) and from the Ubon Ratchathani (n=60) provinces.

2.2 Studied Tools

The general information questionnaire consisted of questions on gender, age (years), congenital disease, agricultural work experience, and lifting and moving activities. In this study, the work activity that had the greatest effect on pain and fatigue was the rubber tapping activity.

Body discomfort was evaluated according to the results of the Musculoskeletal Disorders Severity and Frequency Questionnaire (MSFQ). According to a study on rubber farmers conducted by Chaiklieng (2019), 10 body areas were affected: the neck, shoulders, lower arms, hands and wrists, upper back, lower back, hips and thighs, knees, calves, and feet and ankles.

The discomfort was graded on 5 levels: level 1 was asymptomatic or comfortable (score 0), level 2 was mild discomfort (score 1-2), level 3 was moderate discomfort (score 3-5), level 4 was severe discomfort (score 6-8), and level 5 was very uncomfortable (score 9-16).

The FERA was developed in this study for use as a common tool for observation of a farmer's working posture. The body assessment part is divided into two parts. Part 1 is mainly based on the upper part of the body, namely the shoulders, arms, and back, and Part 2 assesses the lower part of the body. The final scores from assessment of the risk level are divided into the following 5 levels: Acceptable (1 point) means that the performance posture does not need to be improved; Low (2-3 points) means that the performance posture should be improved; Moderate (4-7 points) means that the performance posture should be further improved; High (8-14 points) means that the performance posture should be improved; Very High (≥15 points) means that the performance posture should be improved immediately.

The ergonomics risk assessment form was used to observe working postures by using the REBA technique (Hignett and McAtamney, 2000), and using the rubber farmers' edition from Chaiklieng (2021). The 5 levels were as follows: Level 1 means acceptable, Level 2 means low-risk work requiring minimal monitoring and adjustments, Level 3 indicates moderate-risk work requiring monitoring and adjustment of posture in additional work, Level 4 indicates high-risk work requiring monitoring and adjustment of work posture, and Level 5 indicates very high-risk work requiring immediate monitoring and adjustment of work posture.

3.1 Instrument Structure

The FERA tool was used to observe each farmer's working posture. It is classified into steps according to the upper and lower parts of the body. It consists of an assessment of posture and the duration of work. The farmers were assessed with this tool, as shown in Fig. 1.
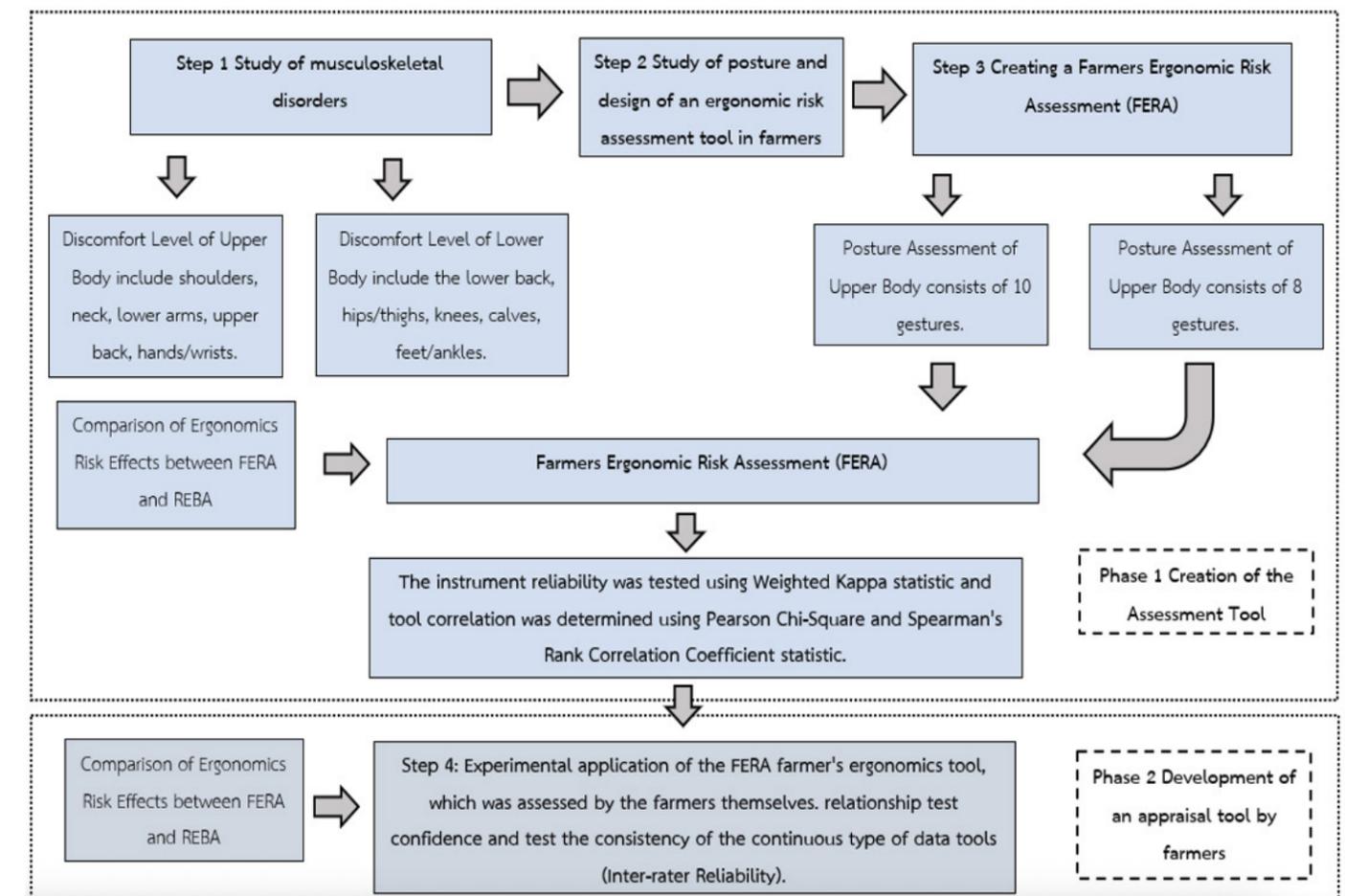

FIGURE 1
Diagram of the development of the Farmers' Ergonomic Risk Assessment (FERA).

3.2 Creation of the FERA Tool

Step 1: Study of the MSDs in terms of the ergonomics of the farmers' working postures and subsequent creation of tools. The study of the subject group was performed in regard to rubber-tapping activities. The body discomfort questionnaire was used to determine relationships. The study was divided into two parts, as follows: levels of upper-body discomfort, i.e, discomfort in the shoulders, neck, lower arms, upper back, and hands/wrists, and levels of lower-body discomfort, i.e, discomfort in the lower back, hips/thighs, knees, calves, and feet/ankles.

Step 2: The study of posture and the design of an ergonomic risk assessment tool for farmers. The study of working behavior in the rubber tapping process, in which all parts of the body are used to perform tasks, and the study of abnormalities in MSDs were considered in the design of an ergonomic risk assessment tool, which could be divided into 10 upper-body and 8 lower-body parts according to the assessment of postures and time of work.

Step 3: Creation of a FERA tool after testing the relationships in the study of MSDs. After the study of posture and the design of an ergonomic risk assessment tool for farmers, the tool was developed to be equivalent to the REBA ergonomics risk assessment by analyzing the data correlation coefficient using Pearson's chi-squared statistic and testing the reliability of the tool using the kappa weighted statistic (weighted kappa).

This led to the creation of a whole-body FERA ergonomic risk assessment tool, which was created by combining upper- and lower-body FERA ergonomics risk scores from a 4×4 risk matrix based on Chaiklieng (2019). The 4x4 risk matrix is used to balance detailed risk assessment with practical simplicity. By offering 16 potential risk combinations, it allows for better, more granular risk estimation and risk prioritization.

3.3 Development of FERA Tool

Development was based on the Phase I study and the test of correlation between the FERA risk assessment tool and the REBA observations assessed by the investigators. To develop a FERA through observation of the working postures of farmers so that they can use it as a self-assessment, the scores are colored in the assessment form so that the farmers can understand them and can choose answers according to the following colors and meanings: green means 1 point, yellow means 2 points, orange means 3 points, red means 4 points. The assessment process by farmers' self-assessment could be performed by following three steps:

Step 1: Posture Assessment

The selection was made according to the performance posture that was found to be most at risk of injury from MSDs. The body assessment was divided into two parts: Part 1: Upper-Body Assessment, which mainly considers the position of the shoulders, arms, and back, as shown in Fig. 2, and Part 2: Lower-Body Assessment, which primarily considers the position of the legs and feet, as shown in Fig. 3. This step has a maximum score of 4 points.

Step 2: Estimating the Duration of Work

In performing the duration of work assessment in Step 2, the body assessment in regard to work duration was divided into two parts: Part 1: Upper-Body Assessment, as shown in Fig. 2, and Part 2: Lower-Body Assessment, as shown in Fig. 3. The posture and work duration assessment was later used in calculations for a combination of upper- and lower-body assessment.

FIGURE 2
Farmers' Ergonomic Risk Assessment for the upper body.

FIGURE 3
Farmers' Ergonomic Risk Assessment for the lower body.

Step 3: Additional Score to Risk Posture and Work Duration According to Force Effort, Repeated Posture, and Twist Application

The modification score from adding to the previous steps was divided into three parts: Part 1: Force effort +1 means less than 5 kg of effort, +2 means between 5 and 10 kg of effort, and +3 means more than 10 kg of effort; Part 2: The posture is repeated or the wrist is used repeatedly or any part is used more than 4 times in 1 minute; and Part 3: +1 means twisting/turning of the wrist or neck or any other joint while working. This step has a maximum score of 5, as shown in Fig. 4. In the ergonomics risk assessment process, the farmers were either self-assessed or assessed by the investigator.

Step 1: Upper-Body Analysis

Step 2: Lower-Body Analysis

Step 3: Add Score

Part 1 Add Force/Load Score
☐ +1 if load < 5 Kg.
☐ +2 if load 5 to 10 Kg
☐ +3 if load > 10 Kg

Part 2 Add Repetition Score
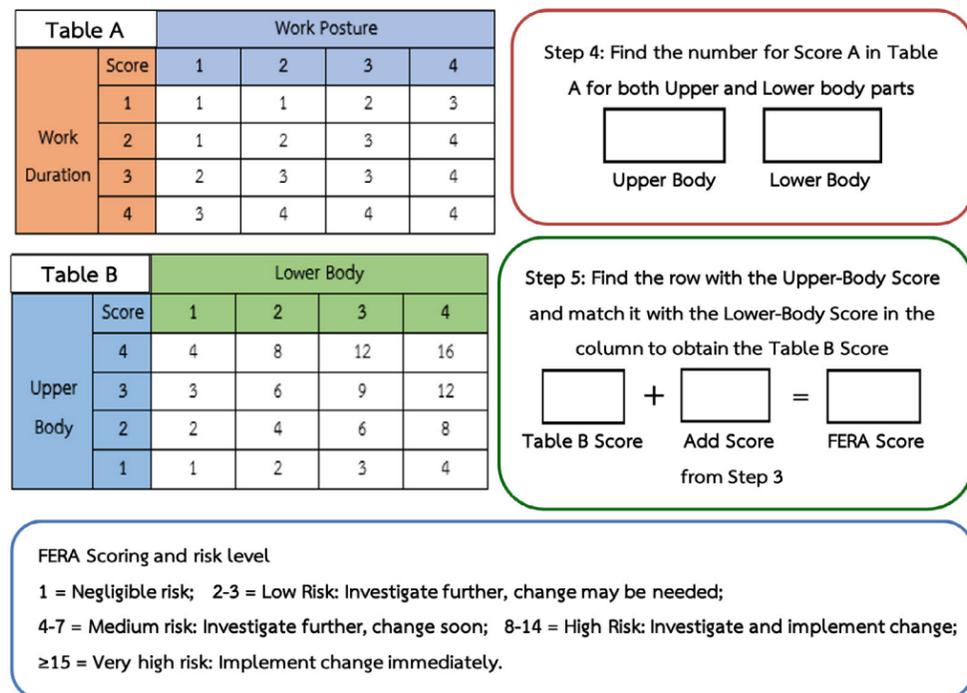☐ +1 if posture or movement of wrist or any part of the body is repeated more than 4 times in 1 minute.

Part 3 Add Twisting/Rotation Score
☐ +1 if wrist or neck or any part of the joint is twisted/rotated

FIGURE 4
Steps 1 to 3 of Farmers' Ergonomic Risk Assessment.
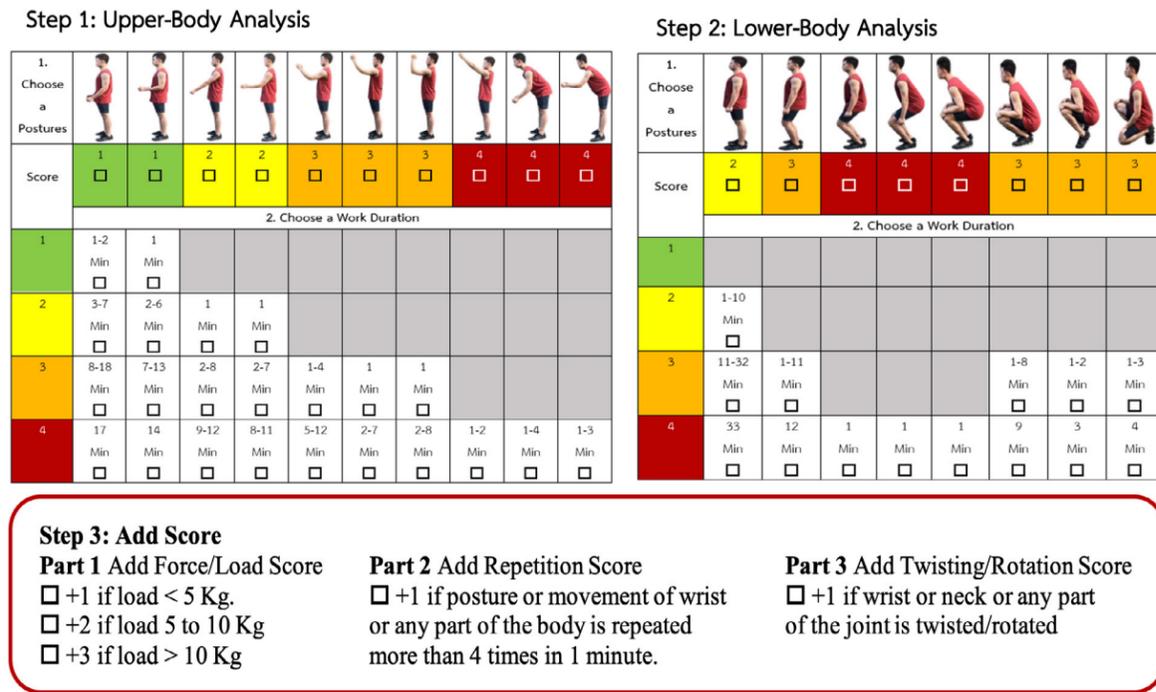
For risk assessment (steps 4-5), the investigator summarized the scores, assessing ergonomic risks from the upper and lower body, from Step 1 to Step 2, using Table A for postural assessment and performance duration. Meanwhile, the whole-body score of the upper and the lower body risk score was calculated using Table B.

The 4x4 upper body (in column) and lower body (in row) risk matrix at this stage had a maximum score of 16, which was finally added with the scores from Step 3 to obtain the highest score of 21, and was divided into 5 risk levels, as shown in Fig. 5.

FIGURE 5
Table A: Posture and work duration, Table B: the risk matrix of the upper- and lower-body, and risk level classification of Farmers' Ergonomic Risk Assessment (FERA).

Table A

	Score	Work Posture 1	2	3	4
Work Duration	1	1	1	2	3
	2	1	2	3	4
	3	2	3	3	4
	4	3	4	4	4

Step 4: Find the number for Score A in Table A for both Upper and Lower body parts

Upper Body ☐   Lower Body ☐

Table B

	Score	Lower Body 1	2	3	4
Upper Body	4	4	8	12	16
	3	3	6	9	12
	2	2	4	6	8
	1	1	2	3	4

Step 5: Find the row with the Upper-Body Score and match it with the Lower-Body Score in the column to obtain the Table B Score

Table B Score ☐ + Add Score from Step 3 ☐ = FERA Score ☐

FERA Scoring and risk level
1 = Negligible risk;   2-3 = Low Risk: Investigate further, change may be needed;
4-7 = Medium risk: Investigate further, change soon;   8-14 = High Risk: Investigate and implement change;
≥15 = Very high risk: Implement change immediately.

The full version of the FERA used in this study is shown in Fig. 6 and FERA tool in Excel sheet (Supporting Material).

Instructions: Please look at the pictures below and fill in ☐ for the postures, work duration, and added scores (Step 1 to 3) by considering the most risky posture regarding injury or musculoskeletal disorders.
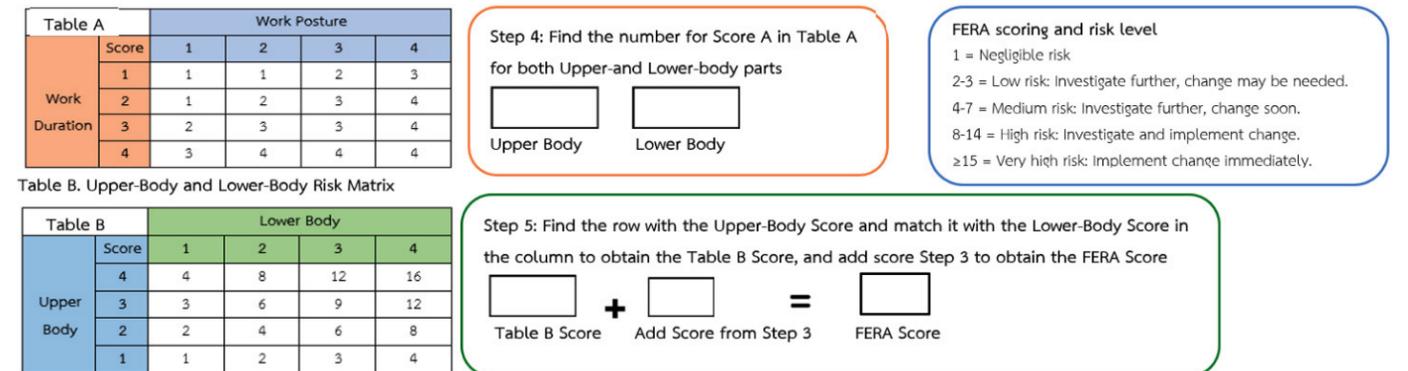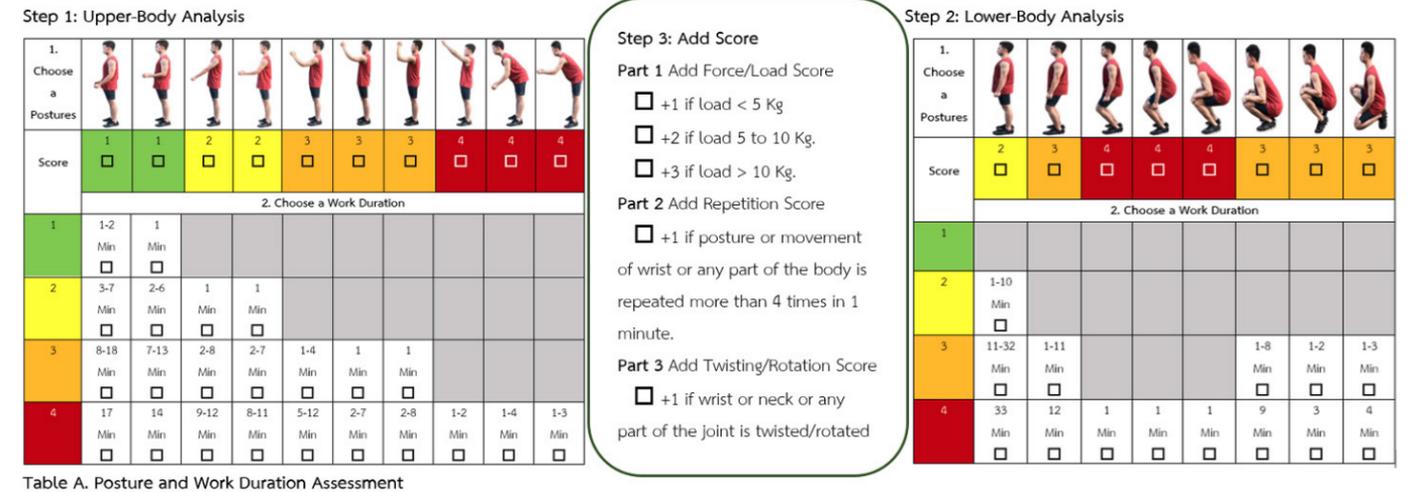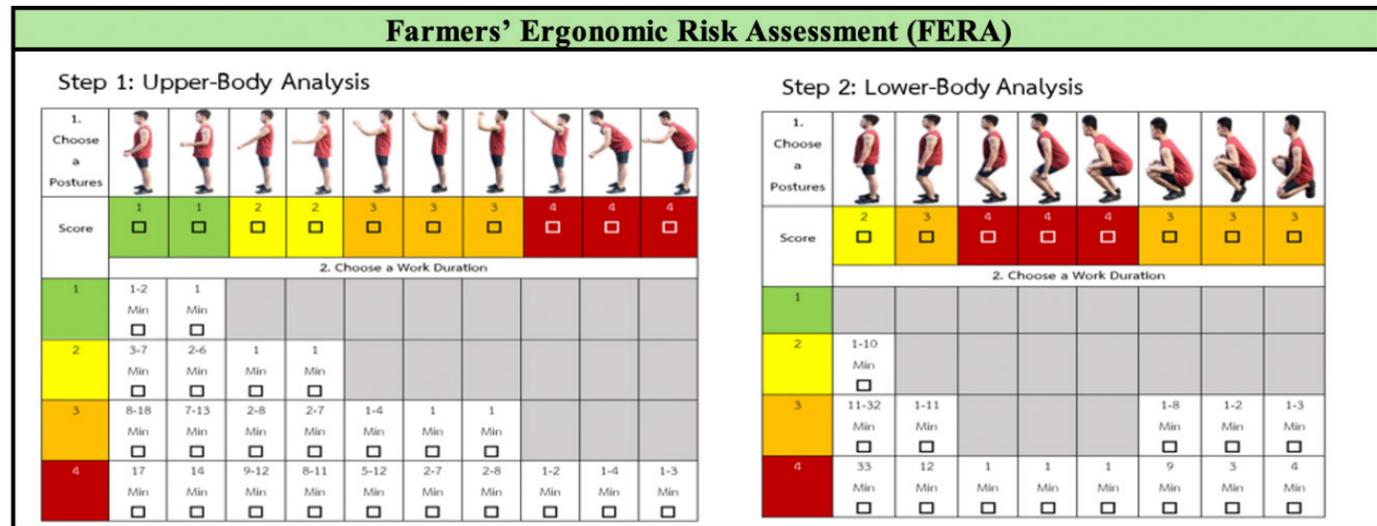

Table A. Posture and Work Duration Assessment

Table B. Upper-Body and Lower-Body Risk Matrix

FIGURE 6
Farmers' Ergonomic Risk Assessment (FERA).

3.4 Data Analysis

The data was analyzed using descriptive statistics with the STATA Version 11.0 program. Numbers and percentages are presented to describe general information and the level of body discomfort. The level of ergonomic risk was analyzed using Spearman's rank correlation coefficient statistic. The correlation between FERA ergonomics risk and REBA ergonomics risk was tested at a significance level of 0.05, and confidence was tested using the weighted kappa statistic and inter-rater reliability testing. This research has been approved by the Human Research Ethics Committee at Khon Kaen University, No. HE642272.

Farmers' Ergonomic Risk Assessment (FERA)

Step 1: Upper-Body Analysis

Choose a Postures									
Score	1 ☐	1 ☐	2 ☐	2 ☐	3 ☐	3 ☐	3 ☐	4 ☐	4 ☐	4 ☐

2. Choose a Work Duration

1	1-2 Min ☐	1 Min ☐						
2	3-7 Min ☐	2-6 Min ☐	1 Min ☐	1 Min ☐				
3	8-18 Min ☐	7-13 Min ☐	2-8 Min ☐	2-7 Min ☐	1-4 Min ☐	1 Min ☐	1 Min ☐	
4	17 Min ☐	14 Min ☐	9-12 Min ☐	8-11 Min ☐	5-12 Min ☐	2-7 Min ☐	2-8 Min ☐	1-2 Min ☐	1-4 Min ☐	1-3 Min ☐

Step 2: Lower-Body Analysis

Choose a Postures							
Score	2 ☐	3 ☐	4 ☐	4 ☐	4 ☐	3 ☐	3 ☐	3 ☐

2. Choose a Work Duration

1						
2	1-10 Min ☐					
3	11-32 Min ☐	1-11 Min ☐			1-8 Min ☐	1-2 Min ☐	1-3 Min ☐
4	33 Min ☐	12 Min ☐	1 Min ☐	1 Min ☐	1 Min ☐	9 Min ☐	3 Min ☐	4 Min ☐

Step 3: Add Score		
Part 1 Add Force/Load Score **1**	Part 2 Add Repetition Score **1**	Part 3 Add Twisting/Rotation Score **1**

Step 4: Find the number for Score A in Table A for both Upper and Lower body parts	
Upper Body Score **4**	Lower Body Score **4**

Step 5: FERA Score			
Table B score (UB *LB)	**16**	Add Score (Step 3)	**3** Final FERA Score **19**

Instructions: Step 1. The body assessment was divided into two parts as follows: Part 1: Upper-Body Assessment, which mainly considers the position of the shoulders, arms, and back, and Part 2: Lower-Body Assessment, which primarily considers the position of the legs and feet. This step has a maximum score of 4 points. Select from the dropdown menu.

Step 2. Estimating the duration of work: Work duration was divided into two parts: Part 1, Upper-Body Assessment, and Part 2, Lower-Body Assessment. Select from the dropdown menu.

Step 3. Additional score to risk posture and work duration according to force effort, repeated posture, and twist application: The modification score from adding to the previous steps was divided into three parts as follows: Part 1: Force effort +1, means less than 5 kg of effort, +2 means between 5 and 10 kg of effort, and +3 means more than 10 kg of effort, Part 2: The posture is repeated or the wrist is used repeatedly or any part is used more than 4 times in 1 minute, and Part 3: +1 means twisting/turning of the wrist or neck or any other joint while working. This step has a maximum score of 5. Select from the dropdown menu for each Part. If N/A, select 0.

Step 4. Find the number for Score A in Table A for both Upper and Lower body parts and select from the dropdown menu.

Step 5. The tool will automatically calculate the FERA score for you. The final **FERA score** is color-coded based on the risk level.

FIGURE 7

Farmers' Ergonomic Risk Assessment (FERA)Tool

Step 3: Add Score

Part 1 Add Force/Load Score
☐ +1 if load < 5 Kg.
☐ +2 if load 5 to 10 Kg
☐ +3 if load > 10 Kg

Part 2 Add Repetition Score
☐ +1 if posture or movement of wrist or any part of the body is repeated more than 4 times in 1 minute.

Part 3 Add Twisting/Rotation Score
☐ +1 if wrist or neck or any part of the joint is twisted/rotated

Table A — Work Posture

	Score	1	2	3	4
Work Duration	1	1	1	2	3
	2	1	2	3	4
	3	2	3	3	4
	4	3	4	4	4

Step 4: Find the number for Score A in Table A for both Upper and Lower body parts

[ ] Upper Body   [ ] Lower Body

Table B — Lower Body

	Score	1	2	3	4
Upper Body	4	4	8	12	16
	3	3	6	9	12
	2	2	4	6	8
	1	1	2	3	4

Step 5: Find the row with the Upper-Body Score and match it with the Lower-Body Score in the column to obtain the Table B Score

[ ] + [ ] = [ ]
Table B Score   Add Score from Step 3   FERA Score

FERA Scoring and risk level

1 = Negligible risk;   2-3 = Low Risk: Investigate further, change may be needed;

4-7 = Medium risk: Investigate further, change soon;   8-14 = High Risk: Investigate and implement change;

≥15 = Very high risk: Implement change immediately.

4.1 Characteristics of Agriculturists

During the study phase of tool creation, the subjects were rubber farmers in the Udon Thani Province. It was found that most farmers were male (58.30%), with a median age of 49 years (minimum age of 22 years, maximum age of 70 years) and a median work experience of 15 years (minimum of 3 years, maximum of 50 years). Most of them had no underlying disease (78.30%), lifted and moved heavy objects (91.70%), and performed rubber tapping activity that led to fatigue (96.70%). During the study phase of FERA tool development, 60 rubber farmers in the Ubon Ratchathani province participated as subjects. It was found that most subjects were male (58.30%), with a median age of 49 years (ranging from 25 to 70 years), and a median work experience of 20 years (ranging from 4 to 50 years). Most of them had no underlying disease (80.00%), with the largest proportion consisting of those who lifted heavy weights (86.70%).

4.2 Musculoskeletal Disorders Severity and Frequency Questionnaire (MSFQ)

Regarding the severity of MSDs, it was found that the intensity of pain increased depending on the body part. Farmers had the most pain in the upper back area, followed by the shoulder area and the feet and ankles. Regarding the frequency of MSDs, it was found that a higher frequency of pain also depended on the body part. Farmers had the most frequent pain in the areas of the shoulders and upper back, followed by the neck, hands and wrists, lower back, calves and hips, and forearms. When assessing the level of discomfort in the body parts of rubber farmers by multiplying the severity by the frequency, it was found that farmers had felt unwell to a greater extent. Discomfort was found most commonly in the shoulders, upper back, and hands and wrists, followed by the forearms and neck (Table 1).

The level of discomfort in the body				
Body parts	Low	Moderate	Severe	Very severe	Severe to very severe
neck	2 (33.30)	16 (26.70)	28 (46.70)2	14 (23.30)	42 (70.00)3
shoulder	0 (0.00)	16 (26.70)	28 (46.70)2	16 (26.60)	44 (73.30)1
upper back	0 (0.00)	16 (26.70)	26 (43.30)3	18 (30.00)	44 (73.30)1
forearm	0 (0.00)	17 (28.40)	29 (48.30)1	14 (23.30)	43 (71.60)2
hand and wrist	1 (1.7)	15 (25.00)	29 (48.30)1	15 (25.00)	44 (73.30)1
lower back	1 (1.7)	26 (43.30)2	12 (20.00)	21 (35.00)2	33 (55.00)
hip	2 (3.30)	25 (41.70)3	11 (18.30)	22 (36.70)1	33 (55.00)
knee	1 (1.7)	29 (48.30)1	9 (15.00)	21 (35.00)2	30 (50.00)
calf	3 (5.00)1	24 (40.00)	12 (20.00)	21 (35.00)2	33 (55.00)
feet and ankles	2 (3.30)	26 (43.30)2	12 (20.00)	20 (33.30)3	32 (53.30)

TABLE 1
Number and percentage of rubber plantation farmers classified by the degree of discomfort (n = 60).
Note: *1, 2, 3 refer to the body part with the highest proportion, ranked first, second and third, respectively.*

4.3 Ergonomics Risks

The results of the FERA ergonomics risk assessment found that 43.30% of the sample group had the highest level of FERA ergonomics risk, followed by 33.30% who had a high risk, and 23.40% who had a reasonable risk. The results of the REBA ergonomics risk assessment found that 43.30% had the highest level of REBA ergonomic risk, followed by 35.00% who had a high risk, and 21.70% who had a medium risk.

4.4 Relationship Between FERA Ergonomics Risk and REBA Ergonomics Risk

When considering the relationship between FERA ergonomics risk and musculoskeletal discomfort, using Spearman's rank correlation coefficient at a significance level of 0.05, it was found that FERA ergonomics risk was statistically associated with REBA (Rho=0.863, p-value< 0.001) (Fig. 8). The intra-rater reliability of the assessors was 0.995, and the reliability of the farmers was 0.977, while the inter-rater reliability between the assessors and the self-assessment of the farmers was 0.971.
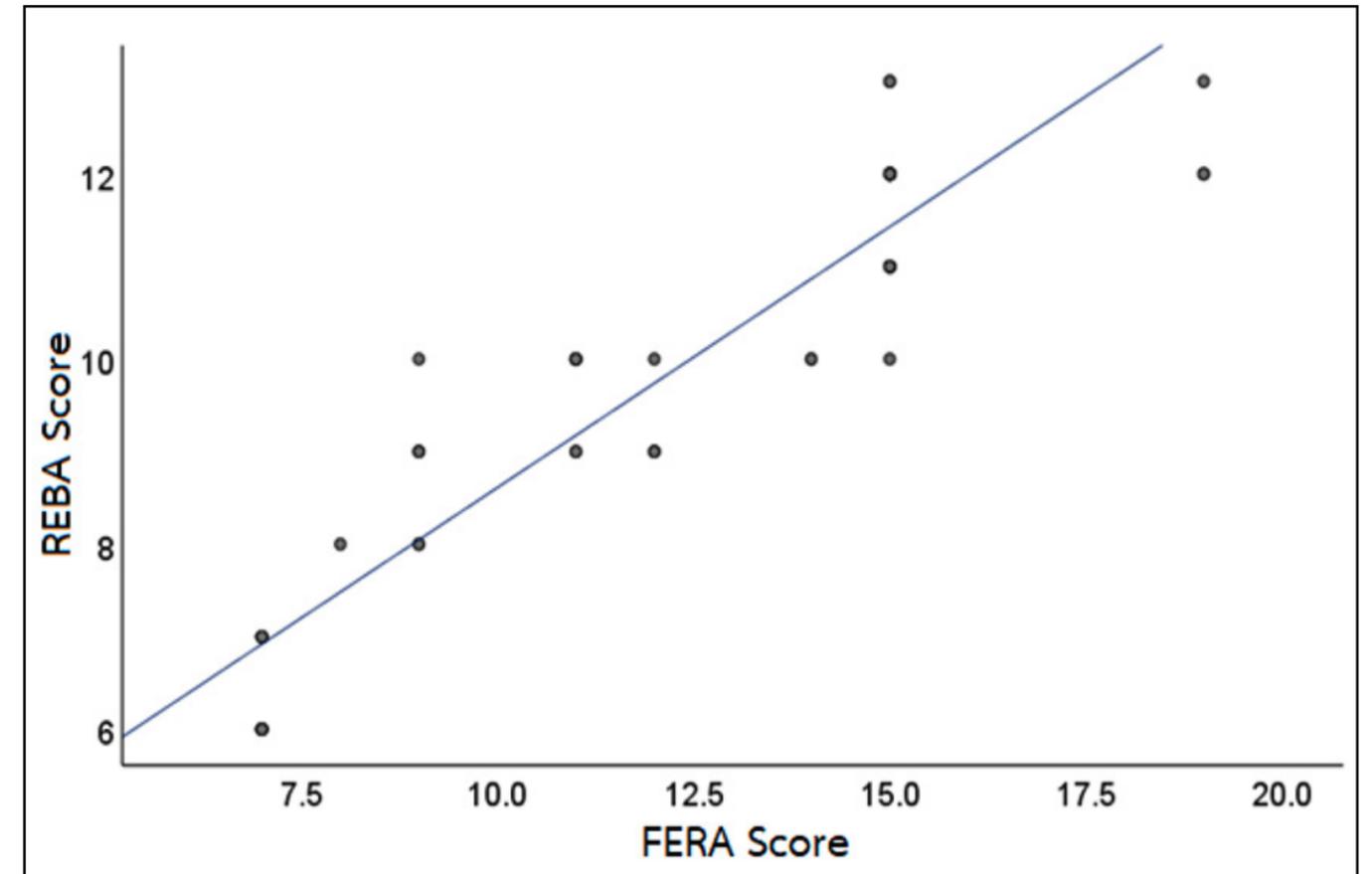

FIGURE 8
Linear correlation between the REBA ergonomics risk score and the FERA whole body ergonomics risk score (Rho=0.863, p-value< 0.001).

DISCUSSION

According to the body discomfort reported by rubber farmers, discomfort was most commonly found in the shoulders, upper back, and hands and wrists of the farmers. During work, the arm is in an exerted posture due to rubber tapping being performed at a high level with repetitive wrist or neck movements, resulting in pain in those areas. This finding is consistent with a study on musculoskeletal discomfort classification by body part, which revealed a high level of susceptibility, with the highest level of discomfort observed in the hand and wrist area (Chaiklieng, 2021). In a previous study of rubber farmers in the Ubon Ratchathani Province, it was found that most farmers experienced moderate discomfort in the hand and wrist areas, followed by the knees and upper back (Khanaphan et al., 2019). This could be supported by the results of a study on MSD prevalence, which showed a high incidence rate of MSDs compared to other occupational diseases during the previous 3 years (Chaiklieng et al., 2022).

The FERA tool is primarily used to assess the tapping motion, as rubber tapping is an activity that utilizes all parts of the body and is expected to result in MSDs. The REBA risk assessment indicated that the posture should be improved immediately. The result is consistent with the previous report on the ergonomic risk of rubber farmers in the Ubon Ratchathani Province, which used REBA in the rubber tapping process (Khanaphan et al., 2019).

The risk outcome from the REBA tool had a statistically significant association with that of the FERA tool, indicating a warning of MSDs in that area. Due to the nature of the work, which leads to exertion in the arm with repeated short twitching, as well as a working posture that includes bending down and tiptoeing, such a posture may affect the MSDs among such farmers. It might explain why rubber tapping farmers had the highest levels of discomfort in the lower back, calves, knees, and feet (Chaiklieng, 2021). Moreover, similar discomfort was also found in various areas of Thai agriculturists and various cultivation activities in upper northeastern Thailand (Poochada et al., 2022).

The FERA tool is derived from the upper- and lower-body posture assessment by using the risk matrix combination that was found to have a significant relationship with the REBA level. The FERA risk assessment, as well as the REBA risk assessment, resulted in a very high level of risk; therefore, it can be confirmed that farmers had a very high-risk posture. This development tool for assessing ergonomic risk of working postures in farmers is an easy-to-use assessment and can be used as a specific tool for assessing farmers' motion during work performance. It is the proposed choice to assess health risk in the MSDs surveillance program as the previous occupational health risk assessment on MSDs was applied to various occupations to predict the MSD risk both in farmers (Chaiklieng, 2021), and industrial workers (Chaiklieng, 2019). The tool was developed for simplicity and to help address the farmers' ergonomic risk assessment needs.

The FERA tool is recommended as the specific tool for the farmers' ergonomic risk approach in the occupational risk matrix, rather than using REBA, which is not specifically tailored to farmers' risk assessment. There should be further investigation and application for development so that the self-assessment technique can be effectively utilized in the proposed tool among farmers engaged in various types of agricultural activities.

Although the tool was developed to assess farmers' ergonomics risks, it can be used in other industries. The research team is planning follow-up studies.

SUPPORTING MATERIALS

S1. Farmers' Ergonomic Risk Assessment (FERA tool).xlsx

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